AD-A199 515

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	PAGE	Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; Distribution Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	

4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFGL-TR-88-0237	5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Air Force Geophysics Laboratory	6b. OFFICE SYMBOL (If applicable) LYS	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Hanscom AFB Massachusetts, 01731-5000		7b. ADDRESS (City, State, and ZIP Code)

DTIC
SELECTE
SEP 3 0 1988
S D

8a. NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Geophysics Laboratory	8b. OFFICE SYMBOL (If applicable) LYS	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code) Hanscom AFB Massachusetts, 01731-5000	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO. 62101F	PROJECT NO. 6670	TASK NO 17	WORK UNIT ACCESSION NO. 06

11. TITLE (Include Security Classification)
An Extension of the Split Window Technique for the Retrieval of Precipitable Water: Experimental Verification.

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT Reprint	13b. TIME COVERED FROM_____ TO_____	14. DATE OF REPORT (Year, Month, Day) 1988 September 23	15. PAGE COUNT 5

17.	COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Remote Sensing, Satellite Meteorology, Retrieval Methodology, Water Vapor

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The split window technique has been demonstrated to be a viable method of removing effects of atmospheric attenuation in order to make a more accurate estimate of surface properties. This technique has also been used to estimate low level water vapor fields. In this paper we make an extension to the split window technique such that it is possible to estimate total precipitable water.

The essence of the split window technique is making observations of the earth in two differentially absorbing windows. We extend this technique by making observations in the split window under conditions where the atmospheric contribution to the upwelling radiance is essentially invariant, but the surface contribution changes markedly. Under these conditions it is possible to write a set of simultaneous equations and solve them for the transmittance at the two frequencies of the split window, and from those deduce the quantity of the primary absorber, water vapor. The conditions under which this extension is valid basically fall under two categories; that of variation in time, and that of variation in

(Cont'd)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☑ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Thomas J. Kleespies	22b. TELEPHONE (Include Area Code) (617)377-3136	22c. OFFICE SYMBOL AFGL/LYS

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

19: Cont

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during the heating cycle of the day would be one example. Another would be observations
from either a geosynchronous or polar orbiting satellite of immediately adjacent land and
water surfaces with contrasting skin temperatures.
    This paper will present experimental verification of this extension to the split window
technique utilizing the Visible Infrared Spin Scan Radiometer (VAS) and the Advanced
Very High Resolution Radiometer (AVHRR).

AFGL-TR-88-0 _(illegible)_

An Extension of the Split Window Technique for the Retrieval of Precipitable Water: Experimental Verification

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1.0 Introduction

The "split window" technique was originally derived for the determination of surface skin temperature, specifically sea surface temperature (Anding and Kauth, 1969). The technique makes use of two differentially absorbing channels in the 11-12 μm region to remove the contaminating effect of water vapor and thus arrives at an improved estimate of the skin temperature. See McMillin and Crosby(1984) for a detailed discussion of the split window technique and an extensive review of the literature.

More recently the channels used for the split window have been applied to the retrieval of precipitable water (Chesters, et al, 1983, Chesters et al, 1987). Whereas these methods seemed to produce internally consistent fields of "low level water vapor", they required *a priori* knowledge of the mean air temperature and empirical adjustment of the absorption coefficients in order to bring the results in agreement with in situ observations.

In this paper we present the results of an extension to the split window technique such that precipitable water can be retrieved with a minimum of *a priori* information.

2.0 Theoretical Discussion

Kleespies and McMillin (1984,1986) have presented a theoretical discussion of this extension to the split window technique. Summarized briefly, this technique assumes that the upwelling longwave infrared radiance is emitted from a plane parallel, non scattering atmosphere in local thermodynamic equilibrium, and that the atmospheric contribution to the upwelling radiance can be described by an effective atmospheric temperature and transmittance. Then if observations are made in the two channels of the split window under two different conditions where the atmospheric contribution to the outgoing radiance is invariant but the surface contribution changes markedly, then a set of four simultaneous equations can be written and solved for the ratio of the transmittance in the split window (see Kleespies and McMillin (1986) for details). These conditions fall under two general categories; that of variation in time, and that of variation in space. Consecutive observations of a land surface from a geosynchronous satellite during the heating cycle of the day would be one example. Another would be observations from either a geosynchronous or polar orbiting satellite of immediately adjacent land and water surfaces with contrasting skin temperatures. The resultant relationship under these conditions is

$$\frac{\tau_{11}}{\tau_{12}} = \frac{T_{11}^1 - T_{11}^2}{T_{12}^1 - T_{12}^2} . \qquad (1)$$

where the superscripts refer to the different viewing conditions and the subscripts refer to the nominal 11 and 12μm channels of the split window. It has been shown that this ratio can be related to "low level water vapor" i.e., precipitable water (Chesters, et al, 1933).

Kleespies and McMillin (1984) discuss the theoretical application of this extension to the Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS), and in their 1986 paper describe, again in theoretical terms, its application to Advanced Very High Resolution Radiometer (AVHRR) split IR window data. In ensuing sections, application of this technique to these two instruments is demonstrated with real data.

3.0 Application to Satellite Radiometer Data

The real test of a retrieval algorithm is to apply it to ...al data and to somehow verify it with ground truth. However this is fraught with difficulties, including cloud contamination, aerosol problems, collocation inaccuracies, and errors in the satellite instrument and the in situ measurements. In the following sections we apply this technique to measurements made with the VAS and the AVHRR. In all cases of comparison with radiosonde transmittance ratio, the transmittance ratio was computed from collocated radiosondes using the wide-band radiative transfer model described by Weinreb and Hill (1980).
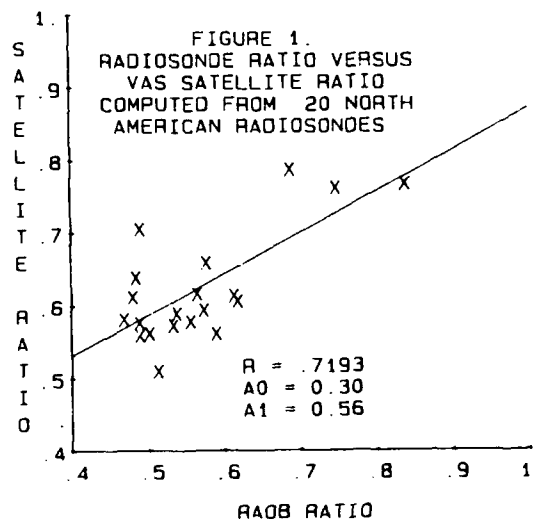
3.1 Application to the VISSR Atmospheric Sounder

Observations were made with the VAS channels 7 and 8 (12.7 and 11.2 μm respectively) over North America on 25 August 1987. Multispectral imagery were acquired on the AFGL Interactive Meteorological System (AIMS) (Gustafson et al, 1987) at hourly intervals from 11:30 UT to 17:30 UT. This works out approximately from just before local sunrise in the mid-United States to just after local noon on the east coast. In order to achieve the contrasting surface contribution to the outgoing radiance, while minimizing the effects of surface obscuration due to convective cloudiness in the local late morning and early afternoon, a variety of time intervals were tested with the optimal interval subjectively selected to be from 1130-1530 UT. Typical brightness temperature increases due to diurnal heating of the surface during this interval were 5-10 K. Since the VAS oversamples along the scan line by a factor of 2:1 for band 8 and 4:1 for band 7, and the band 7 detector linear dimensions are twice that of band 8, a total of 6 pixels from band 7 were averaged to make one band 7 "retrieval spot" and 6 pixels from each of two lines of band 8 (a total of 12 pixels) were averaged to make one band 8 "retrieval spot". If the average brightness temperature in either

channel were less than 273 K at either of the two times, the retrieval spot was assumed to be cloudy and was discarded. Furthermore, if the standard deviation of the brightness temperatures that went in to making the retrieval spot were greater than about 1.5 K for either time, the spot was assumed to be partly cloudy and was discarded.

The transmission ratio was computed for each non-discarded retrieval spot using Eq. (1). Examination of pseudo-imagery of this transmission ratio revealed that while interesting mesoscale features were apparent in this imagery, further spatial averaging was required before quantitative comparisons could be attempted.
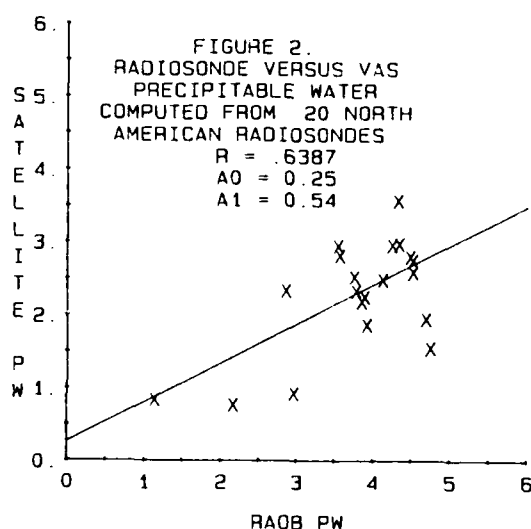
Collocations were performed on launch sites of the 1200 UT radiosondes on 25 Aug 1987. Statistics were computed on the non-discarded transmittance ratios from a 9x9 box of transmittance ratios centered on the radiosonde site. Those transmittances outside of one standard deviation from the mean of the ratios were discarded and the mean was recomputed. This filtered mean was compared with the radiosonde only if the the resulting number of retrieval spots exceeded ten. The comparison between the transmittance ratio derived from the VAS and that derived from the radiosonde is presented in Figure 1.

FIGURE 1.
RADIOSONDE RATIO VERSUS
VAS SATELLITE RATIO
COMPUTED FROM 20 NORTH
AMERICAN RADIOSONDES

R = .7193
A0 = 0.30
A1 = 0.56

SATELLITE RATIO

RAOB RATIO

Precipitable water was computed from the mean ratio by adapting the method of Chesters et al (1987) to this problem

$$PW = 1/\Delta\alpha \left\{ 1/sec\ \theta\ ln[\tau_{11}/\tau_{12}] - \Delta\kappa \right\}$$

2)

where $\Delta\kappa = 0.051$ and $\Delta\alpha = .136$ are differential absorption coefficients, θ is the local zenith angle and the τ's are the transmittances. The comparison between the precipitable water derived from Eq. (2) and the radiosonde precipitable water is given in Figure 2.

FIGURE 2.
RADIOSONDE VERSUS VAS
PRECIPITABLE WATER
COMPUTED FROM 20 NORTH
AMERICAN RADIOSONDES
R = .6387
A0 = 0.25
A1 = 0.54

RAOB PW
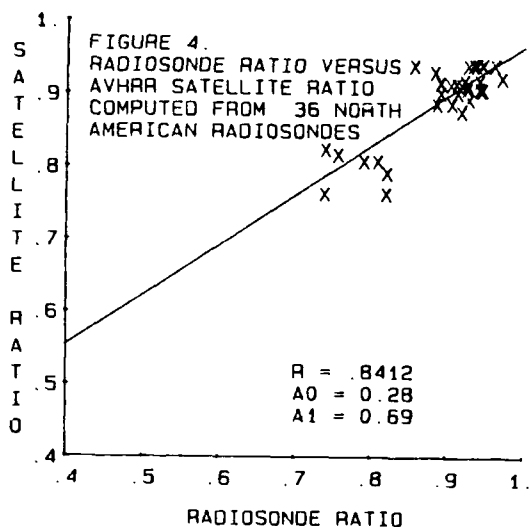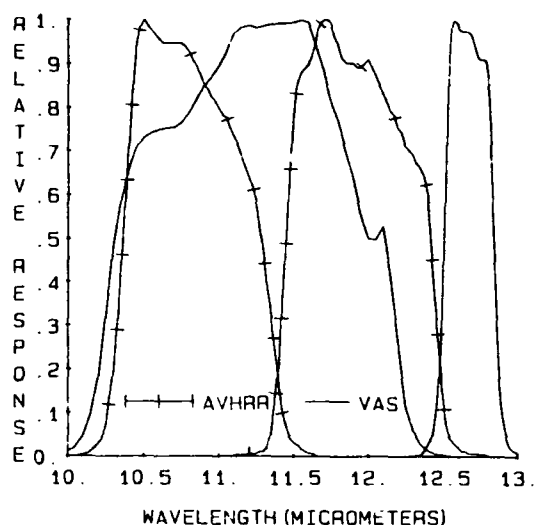
3.2 Application to the AVHRR

Global Area Coverage (GAC) data from the AVHRR were collected from NOAA-7 for 11 June 1982. GAC data has a nominal resolution of 4 km and is distinguished from the nominal AVHRR sensor 1 km resolution by the fact that four pixels are averaged along scan and four scans are skipped to make a GAC scan line. Bands 4 and 5 have the nominal wavelength of 10.7 and 11.8 μm respectively which correspond only approximately to those of the VAS (see Fig. 3). Nighttime data over North America was used in order to be as close as possible to radiosonde launch time and in order to avoid convective cloudiness. The orbits were from four hours to one hour prior to synoptic time. Cloud free areas were selected at the AIMS workstation by examining 24-bit multispectral imagery

created from AVHRR bands 3, 4 and 5 (d'Entremont and Thomason, 1987). In this imagery opaque clouds appear white, low clouds and fog appear bright red against a brown background, and thin cirrus appears cyan, yielding a fairly unambiguous rendition of clear/cloudy regions. Contrasting surface temperatures were determined by selecting a body of water (lake, river, coastline) which at nighttime was relatively warm compared to the surrounding countryside. A 3×3 array of GAC spots were selected for both the warm water surface and the cooler countryside surrounding it. Since many of these water surfaces did not fill the 3×3 array of GAC pixels, a method was developed to determine the "best" combination of warm and cold brightness temperatures. Typical brightness temperature differences were about 5 K. A comparison of two ensembles of 3×3 arrays yields 81 possible combinations. The brightness temperature differences between these 81 combinations were sorted for each of the two channels. The sum of the rank order of the pixel pairs between the two scenes and the two channels was used as a quality measure, the idea being to maximize the brightness temperature difference between the warm and the cold scenes for both channels. Since there is a danger that sub-pixel cloudiness in one scene but not the other which would contribute to an excessively high quality measure, the transmission ratios computed from Eq. (1) were averaged for the top 10 quality measures.

The method presented by Chesters (1983) for computing precipitable water from transmission ratio applies only to the VAS instrument. Whereas it can be adapted to the AVHRR, time limitations for publication in these preprints allow only an indirect comparison with in situ measurements. Rather than compare the radiosonde precipitable water with AVHRR precipitable water using an untested relationship between precipitable water and transmission ratio, it was deemed most prudent to compare directly between the satellite and the radiosonde transmission ratios.

Radiosondes from 1200 UT on 11 June 1982 over North America were collected from the AFGL McIDAS upper air archive. Collocations were made to the closest radiosonde within 300 km of the satellite observation. The comparison between the modeled transmittance ratio and that computed from Eq. (1) for the AVHRR is given in Fig. 4.

FIGURE 3.
RELATIVE INSTRUMENT RESPONSE
FOR VAS AND AVHRR
SPLIT WINDOW CHANNELS

WAVELENGTH (MICROMETERS)

FIGURE 4.
RADIOSONDE RATIO VERSUS
AVHRR SATELLITE RATIO
COMPUTED FROM 36 NORTH
AMERICAN RADIOSONDES

R = .8412
A0 = 0.28
A1 = 0.69

RADIOSONDE RATIO

4 0 Discussion

The correlation between the VAS transmittance ratio and that computed from collocated radiosondes is about 0.72 . The correlation between the AVHRR ratio and the radiosonde ratio is an even more respectable 0.84 . The precipitable water computed from the VAS transmittance ratio had a correlation coefficient of about 0.64 when compared with the radiosonde precipitable water. Chesters et al (1983) reported a lesser correlation with their initial study, (r=0.43), even though they used ancillary information in the form of the atmospheric temperature averaged over a number of radiosonde sites. In their 1987 paper they substantially improved on this figure by using empirical adjustments to the absorption coefficients and by modifying the atmospheric temperature used in their algorithm. The method presented here requires no ancillary information. However, examination of Figures 1, 2 and 4 indicate that the line of best fit in each figure does not have a zero intercept or a slope of unity. It is clear that empirical adjustments are warrented to help remove the systematic bias which is evident in these figures.

Perhaps the greatest uncertainty in retrieving precipitable water from satellite observations lies in determination of the atmospheric absorption coefficients for these channels. Since these channels are quite broad and water vapor is a significant absorber in this region (the water vapor continuum is poorly characterized), absorption uncertainties dominate errors in the retrieval process. The focus of Chesters et al (1987) is the empirical adjustment of the absorption coefficients to optimize the precipitable water retrievals. Barton (1985) reports similar problems with his sea surface temperature determination.

Another major source of concern in application of this technique has to do with instrument noise. Since Eq. (1) deals with the ratio of a difference in the brightness temperatures, this method is quite sensitive to errors in the measurements. The VAS has a nominal NEΔT of 0.25 for these channels. The AVHRR has a NEΔT of 0.12 for its split window channels. Just on this figure of merit, the AVHRR would seem to be better suited for this purpose since a smaller brightness temperature difference would be required for Eq. (1) in order to minimize the effect of instrumental noise. However, it is much easier to

obtain the desired change in scene brightness temperature by observing diurnal temperature changes from geosynchronous orbit than searching for contrasting skin temperatures from polar orbit.

There is a further problem with the VAS instrument. We have noticed "streaking" in the band 7 imagery. Analysis of these streaks indicate that the brightness temperature from scan line to scan line can jump by as much as ± 4 deg K compared to surrounding scan lines. Menzel (1987, private communication) indicates that one of the two large HgCdTe detectors on the VAS instrument is not well calibrated, but it is not known which. This type of calibration problem will probably preclude operational use of the algorithm presented in this paper. However, the imager to be flown on GOES NEXT is very similar to the AVHRR, with planned NEΔT even better than the present AVHRR (Koenig, 1987). It is anticipated that with the launch of GOES NEXT, a thorough evaluation of this method can be made.

5.0 Acknowledgements

The authors wish to thank Mssrs. Mike Weinreb and Mike Hill of NOAA/NESDIS for providing the radiative transfer code used in this study, and Dr. Dennis Chesters for providing a pre-publication copy of his 1987 article. The authors also express their appreciation to Mr. Robert d'Entremont of AFGL Satellite Meteorology Branch for his assistance with the AVHRR GAC data.

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